1

Introduction

1.1 Scope

This book systematically presents recent developments in hydrodynamics and heat and mass transfer in accelerative boundary layers and film flow. The range of research in this book involves three related parts. The first part is devoted to the presentation of the studies related to accelerating boundary layers. It involves free convection of Newtonian gases and liquids. Also, all temperature-dependent physical properties of fluids are considered for phenomena with large temperature differences. The second part is devoted to the presentation of studies related to accelerating film boiling and condensation of Newtonian fluids. The temperature-dependent physical properties of fluids are considered for phenomena with large temperature differences. In the third part, the development of studies for hydrodynamics and heat transfer for falling film flow of non-Newtonian power-law fluids (FFNF) is presented. The boundary layers and film flows we deal with are all caused by buoyancy or gravity, both of which lead to acceleration of the fluid in boundary layers and film flows. Because of the similar flow situation, the studies in these three parts can be summed up in terms of the laminar free convection film flows caused by acceleration. In addition, even the studies related to the free convection film flows for Newtonian fluids can be taken as a special case of those related to non-Newtonian power-law fluids.

1.2 Application Backgrounds

Heat transfer in boundary layers and film flows caused by acceleration often involves large temperature differences. Its practical applications exist widely in various branches of industry, such as the metallurgical, chemical, mechanical, and food industries. The heat transfer on surfaces of various industrial furnaces (such as boilers, heating, and smelting furnaces) is caused by various forms of free convection under large temperature differences, except for the radiation heat transfer. The heat transfer rate affects the heating process and heat efficiency of the furnaces. On the surface of an ingot mold in metal casting there exists free convection heat transfer, and this transfer affects the solidification and crystalline process and therefore the quality of the product. In the process of the surface hardening of metal, in the initial stage, the film boiling free convection is produced on the surface and in the final stage on the surface there exists liquid free convection. These processes will improve the mechanical function of the metal surface. In the electronic industry, cooling process occurs with free convection on the surface integrated circuits. This cooling process tends to restrict the surface temperature to below the allowable temperature. In addition, it is widely known that film condensation free convection has significant applications in various condensators. The suitable design of the corresponding heating equipment and the optimal control of the corresponding heat transfer depends on correct prediction of these processes related to heat transfer mentioned earlier.

Non-Newtonian power-law fluid behavior is encountered in a great variety of everyday life as well as in industrial operations. By far the largest effort has been devoted to Newtonian fluid mechanics. Recently, modest attention has been devoted to gravity-driven thin film flow of the non-Newtonian power-law fluids, as compared with its Newtonian counterpart. Yet, the free surface flow of the non-Newtonian power-law fluids is a widely occurring phenomenon in various industrial applications, for instance in polymer and plastics fabrication, food processing, and in coating equipment. The heat transfer from the solid surface to a liquid film is of practical importance in various types of heat and mass transfer equipment such as coolers, evaporators, and trickling filters. The obvious advantage with the falling film principle is that the short residence time for heat transfer can be realized, which is most desirable for heat-sensitive materials.

1.3 Previous Developments

1.3.1 For Accelerating Boundary Layers and Film Flow of Newtonian Fluids

The basic ideas underlying the approximation that yield the boundary layer equations were developed by Prandtl [1]. The essential idea is to divide a flow into two major parts. The larger part concerns a free stream of fluid far from any solid surface. The smaller part constitutes a thin layer next to a solid surface in which the effects of molecular transport properties (viscosity and thermal conductivity) are considered using some approximation. Prandtl initiated the study of free convection by means of boundary layer theory. For a long time, the study was based on the Boussinesq approximation [2, 3]. In this approximation, the temperature-dependent properties of fluids are neglected in the governing partial equations of the boundary layer, except for density in the buoyancy term of the momentum equation. Pohlhausen [4] solved partly the governing equations of boundary layer. Ostrach [5] supplied a more detailed numerical solution for free convection. Ede [6] also provided a numerical solution for the dimensionless temperature gradient for various values of Prandtl number. LeFevre [7] proposed an approximation for the prediction of the Nusselt number. However, since these research results are based on the Boussinesq approximation, they are only suitable for the case of small temperature difference between the body surface and the ambient fluid. However, for the case of large temperature differences, these results are not appropriate.

Therefore, it is important to study free convection with larger temperature differences, and should include free convection with and without phase change, such as free convection of fluids, film boiling free convection, and film condensation free convection. Free convection with a small temperature difference dealt with by the Boussinesq approximation is only a special case of free convection with larger temperature differences.

Due to the universality of free convection with large temperature, the consideration of variable temperature-dependent properties is very important in the corresponding studies. The earliest theoretical consideration of variable thermophysical properties for free convection is the perturbation analysis of Hara [8] for air. The solution is applicable for small values of the perturbation parameter, $\varepsilon_{\mathrm{H}} = (T_{\mathrm{w}} - T_{\infty})/T_{\infty}$. Tataev [9] also investigated the free convection of a gas with variable viscosity. A well-known analysis of the variable fluid property problem for laminar free convection on an isothermal vertical flat plate has been presented by Sparrow and Gregg [10]. They considered five different gases and provided the corresponding solutions of the boundary layer equations. They proposed a reference temperature and suggested that the problem of variable thermophysical properties can be treated as a constant property problem, i.e., Boussinesq approximation. Gray and Giogini [11] discussed the validity of the Boussinesq approximation and proposed a method for analyzing natural convection flow with fluid properties assumed to be a linear function of the temperature and pressure. Clausing and Kempka [12] reported their experimental study of the influence of property variations on natural convection and calculated it for the laminar region. The Nusselt number Nu_{f} will be a function of Rayleigh number $Ra_{\mathrm{f}}(= Gr_{\mathrm{f}}Pr_{\mathrm{f}})$ only with the reference temperature, T_{f}, taken as the average temperature in the boundary layer.

In [13–22], studies of the effects of variable thermophysical properties of liquid on the laminar free convection with larger temperature difference were carried out. Fujii et al. [13] examined two methods of correlating the effects of variable thermophysical properties on heat transfer for free convection from vertical surfaces in liquids. The first method of correlating the data consisted of using the constant property correlations for the Nusselt number and evaluating all physical properties at a reference temperature, $T_{\mathrm{r}} = T_{\mathrm{w}} - (T_{\mathrm{w}} - T_{\infty})/4$. They noted that the choice of the reference temperature corresponds with the solution provided by two previous studies [14, 15]. The second method that they used to correlate their data for oils was first proposed by Akagi [15] and applies only to liquids for which the viscosity variation is dominant. The similarity analysis of Piau [16] also treated variable property effects in free convection from vertical surfaces with high Prandtl number liquids. It was indicated that the main property variations in water at moderate temperature levels are in the viscosity, μ, and the volumetric coefficient of thermal expansion, β, and that for higher Prandtl number liquids, the variation of β is often negligible. Piau [17] also included the effect of thermal stratification of the ambient fluid in an analysis which also includes variable μ and β for water. Brown [18] used an integral method and studied the effect of the coefficient of volumetric expansion on laminar free convection heat transfer. Carey and Mollendorf [19] have shown the mathematical forms of viscosity variation with temperature and gave similarity solutions for laminar free convection from a vertical isothermal surface in liquids with temperature-dependent viscosity. Sabhapathy and Cheng [20] studied the effects of temperature-dependent viscosity and coefficient of thermal expansion on the stability of laminar free convection boundary-layer flow of a liquid along an isothermal, vertical surface, employing linear stability theory for Prandtl numbers between 7 and 10. Qureshi and Gebhart [21] studied the stability of vertical thermal buoyancy-induced flow in cold and saline water. They showed that the anomalous density behavior of cold water (for example, a density extremum at about 4°C in pure water at atmospheric pressure) has very large effects on flow and transport. Meanwhile, Herwig and Wickern [22] studied the effect of variable thermophysical properties on laminar boundary layer flows.

Different gases and liquids have different thermophysical properties. The effects of the different thermophysical properties on the laminar free convection and heat transfer are complicated. The results reported so far are not convenient for the prediction of free convection heat transfer due to the difficulty of treating the variable thermophysical properties in the governing equations. Consequently, it is necessary to do more research related to rigorous and reliable prediction of heat transfer coefficient of free convection with large temperature differences.

Bromley [23] first treated laminar film boiling heat transfer of saturated liquid around a horizontal cylinder in a pool. Some other researchers [24–30] have analyzed pool film boiling on a vertical plate. However, only a few analyses took into account the temperature dependence of the fluid's thermophysical properties. McFadden and Grash [27] developed the analysis of saturated film boiling in a pool where the temperature dependence of density and specific heat were considered. Nishikawa et al. [28, 29] made an analysis of pool film boiling as a variable property problem on the basis of the two-phase boundary layer theory, considering only the effect of variation of the vapor's thermophysical properties with temperature in the lower range of subcooling, i.e., ($T_s - T_\infty = 0$, 20, 40°C). Herwig [30] provided an asymptotic analysis of laminar film boiling on vertical plate including variable property effect. In fact, the temperature difference between heating surface and bulk liquid may be very large, and the thermophysical property variations of the medium in the condensate and vapor films with temperature can have great influences on the pool film boiling free convection.

For film condensation free convection, Nusselt [31] first treated the condensation of saturated steam on a vertical isothermal flat plate. In his theory the inertia and thermal convection of condensate film, the dependence of the thermophysical properties of the condensate medium on temperature, and the effect of surface tension were all neglected. Bromley [32] and Rohsenow [33] first investigated the effect of thermal convection. Later on, the study of Sparrow and Gregg [34] included the effects of thermal convection and inertia forces in the liquid film by using the boundary layer analysis. Koh et al. [35] further solved numerically a boundary-layer model for both the condensate and vapor films. Chen [36] has considered analytically the effect of thermal convection, inertia, and the interface shear force. On the basis of foregoing studies of the independent-temperature physical properties Drew (see [37]), Voskresenskiy [38], and Labuntsov [39] made relatively simple modifications for variable thermophysical properties. Subsequently, Poots and Miles [40] studied the effects of variable thermophysical properties on laminar film condensation of a saturated steam along a vertical flat plate. They simplified the governing equations of the liquid and vapor phases by neglecting the effects of surface tension at the liquid–vapor interface, and obtained solutions of the resulting ordinary differential equations. Late Stinnesbeck and Herwig [41] provided an asymptotic analysis of laminar film condensation on a vertical flat plate including variable property effect. Based on the research results thus far, it is necessary to provide corresponding correlations for the prediction of heat and mass transfer of the film condensation with the large temperature differences.

Generally, there are two problems that hindered the development of studies of the laminar free convection with single and two-phase boundary layers under large temperature differences. The first difficulty is the traditional Falkner–Skan transformation [42]. With this transformation one encounters a large difficulty in the treatment of variable thermophysical properties. So it is necessary to carry out the study of an improved transformation method in order to suit the development of the free convection with a large temperature differences. The second difficulty is the traditional treatment of the variable thermophysical properties. Since Sparrow and Gregg [10] proposed the treatment model of the variable thermophysical properties with the five different gases in 1958, the treatment method of the variable thermophysical properties has not been improved much. Thus, for a long time, there has been an absence of studies of the free convection with large temperature difference by means of model involving the variable thermophysical properties.

1.3.2 For Gravity-Driven Film Flow of Non-Newtonian Power-Law Fluids

Non-Newtonian power-law fluid behavior has been the subject of many recent books [43–47] and useful numerical calculation techniques for non-Newtonian fluid flow have been reviewed by Crochet and Walters [48] and Crochet et al. [49].

The study of the hydrodynamics of falling film flow of power-law fluids was reviewed by Andersson and Irgens [50]. However, the initial studies were carried out experimentally. The experiments of Astarita et al. [51], Therien et al. [52] and Sylvester et al. [53] all include measurements of film thickness as a function of the volumetric rate. The hydrodynamics of gravity-driven power-law films has been studied theoretically by means of the integral method approach [54–57] and similarity analysis [58,59]. Yang and Yarbrough [54,55] and Narayana Murthy and Sarma [56] extended the conventional integral analysis for Newtonian films to cover power-law fluids. Later, Narayana Murthy and Sarma [57] included the effect of interfacial drag at the liquid–vapor interface in a similar analysis, while Tekic et al. [58] presented results which accounted for the streamwise pressure gradient and surface tension. More recently, Andersson and Irgens [59] explored the influence of the rheology of the film on the hydrodynamic entrance length.

A different approach was adopted by Andersson and Irgens [59,60], namely to divide the accelerating film flow into three regions, the boundary layer region, the fully viscous region and the developed flow region. While the boundary layer region is divided into a developing viscous boundary layer and an external inviscid freestream. They further demonstrated that a similarity transformation exists, such that the boundary layer momentum equation for power-law fluids is exactly transformed into a Falkner–Skan type ordinary differential equation. The resulting two-point boundary-value problem was solved numerically with a standard shooting technique based on classical fourth-order Runge–Kutta integration in combination with a Newton iteration procedure. Numerical results were obtained for values of the power-law index n in the range $0.5 \leq n \leq 2.0$. It was conjectured that converged results could have been obtained also for highly pseudo-plastic fluids, i.e., for $n < 0.5$, by using a different integration technique, for instance a finite-difference scheme.

So far, there has been a lack of research work on heat and mass transfer in falling film flow of power-law fluids in comparison with that on the hydrodynamics. The dissolution of a soluble wall and the subsequent penetration of the solute into the non-Newtonian liquid film were considered by Astarita [61], who provided the mass transfer rate between the wall and the hydrodynamically fully developed film, with an assumption of velocity near the wall to vary linearly with the distance from the wall. Mashelkar and Chavan [62] provided a more general solution of this problem. Van der Mast et al. [63] indicated that for accelerating film flow the heat transfer coefficient for the inlet section considerably higher than further downstream. In this connection, Yih and Lee [64] used an integral method and provided a corresponding solution of the heat transfer in the thermal entrance region of a non-Newtonian, laminar, falling liquid film, without consideration of properties of the non-Newtonian fluids. Narayana Murthy and Sarma [56] provided an integral approach for investigation of the problem of heat transfer for the transition and developed regions of the thin, non-Newtonian falling liquid films. Unfortunately, it is readily verified that their solutions based on the integral methods do not induce to the exact analytic solution. As for the effect of injection/suction on the heat transfer, so far there has been only one study of Pop, Watanabe and Komishi [65] on the steady of laminar gravity-driven film flow along a vertical wall for Newtonian fluids, which is based on Falkner–Skan type transformation.

However, it is seen that even the Falkner–Skan type transformation has its limitations. As we know, it is necessary to introduce a stream function for using the Falkner–Skan type transformation. As a consequence, the variables in the resulting dimensionless governing equations are so abstract that their relationships with the flow variables are complicated. Therefore, it is difficult for the Falkner–Skan type transformation to find solutions to some key problems related to hydrodynamics and heat and mass which are rigorous and convenient for predicting the mass flow rate entrained into the boundary layer at any position of the hydrodynamic entrance region, the critical thickness of the film flow, and the resultant heat and mass transfer. On the other hand, it is very difficult to treat variable thermophysical properties in the models based on the Falkner–Skan type transformation.

1.4 Recent Development

1.4.1 A Novel System of Analysis Models

There is a long history of using Falkner–Skan type transformation for treatment of governing differential equations of the boundary layers and film flows of Newtonian and power-law fluids caused by acceleration. In view of some difficulties produced in using the Falkner–Skan type transformation, a new transformation method, velocity component method, is presented in this book, in which the velocity components are directly transformed instead of inducing the flow function ψ. With this method our new system of theoretical and mathematical models are provided for the laminar free boundary layer of Newtonian fluids, gases by Shang and Wang [66–68] and liquids by Shang, Wang, Wang, and Quan [69], for film boiling by Shang, Wang, and Zhong [70] and condensation by Shang and Adamek [71] and Sang and Wang [72] of Newtonian fluids, and for gravity-driven FFNF by Andersson and Shang [73], Shang and Andersson [74], and Shang and Gu [75], and the earlier difficult situations are avoided. In these models, it is noted that the new variables in the new transformations have obvious physical meanings. Then, by means of the velocity component method, it is convenient to treat the problems of the hydrodynamics and heat and mass transfer, even those with variable thermophysical properties and complicated physical factors. In this book, it can be found that all the theoretical models both for Newtonian and non-Newtonian fluid are based on the same similarity transformation, using the dimensionless velocity component method.

1.4.2 A New Approach for the Treatment of Variable Thermophysical Properties

The effect of large temperature differences on heat transfer of the free convection and accelerating film boiling and condensation reflects the influence of the variable thermophysical properties. The thermophysical properties of most fluids vary with temperature. For gases, although the specific heat varies only slightly with temperature, the variation of other thermophysical properties cannot be neglected. The density varies inversely with the first power of the absolute temperature, and absolute viscosity μ and thermal conductivity λ increase with different powers of the absolute temperature. Generally, for a gas with an increase of the atomic number, the exponent of the power increases. According to the recent study of Shang and Wang [66, 67], a temperature parameter method for the treatment of variable thermophysical properties of gas was presented. For example, if we express the variations of μ and λ with $\mu \propto T^{n_\mu}$ and $\mu \propto T^{n_\lambda}$, respectively, n_μ and n_λ are 0.649 and 0.71 for a monatomic gas Ne, 0.694 and 0.86 for diatomic gas O_2 and, and 0.88 and 1.3 for polyatomic gas CO^2, respectively. In addition, this temperature-dependent thermophysical property is especially pronounced for liquids, even for viscous oils and pseudo plastic-liquids. The μ and λ values of these liquids are highly temperature-dependent, and the Prandtl number thus varies with temperature in the same manner as μ and λ.

With the temperature parameter method the variations of gas thermophysical properties can be described in the form of powers of absolute temperature. Consequently each temperature parameter, i.e., the temperature exponent, represents the variation of the corresponding thermophysical property of gas with temperature. Also, the temperature parameters of thermal conductivity and viscosity for a series of monatomic and diatomic gases, air and water vapor are proposed based on the typical experimental data. In addition, it has been found that the variation of specific heat with temperature of a polyatomic gas is so important that it cannot be neglected in the study of the effect of variable thermophysical properties on the gas free convection. In this context, the temperature parameter of the specific heat was proposed and the effect of variable thermophysical properties on the free convection of polyatomic gas was further studied [67]. All the temperature parameters were obtained rigorously on the basis of the typical experimental data. In addition, Shang and Wang [69] recommended a polynomial method to obtain simple and exact polynomial equations of density and thermal conductivity for treatment of variable thermophysical properties of liquids. In this book it is shown that with the advanced treatment method of variable thermophysical properties combined with the velocity component transformation, the fluid properties of the governing equations can be always transformed into the corresponding physical property factors. Such advanced method for the treatment of variable thermophysical properties has become an important part of the related theoretical models.

1.4.3 Hydrodynamics and Heat and Mass Transfer

Heat and Mass Transfer of Free Convection and Film Flows of Newtonian Fluids

Based on the new theoretical and mathematical models in this book, the studies are devoted to hydrodynamics and heat and mass transfer of fluid free convection, accelerating film boiling and condensation, as well as driven film flow of non-Newtonian power-law fluids. First, a series of developments are shown in the heat and mass transfer of gas free convection, liquid free convection, film boiling, and condensation, which belong to boundary layer and film flows of Newtonian fluids. The related developments on heat and mass transfer shown in this book can be briefly introduced as follows.

The first study is for the heat transfer of free convection of gases [66–68] with consideration of variable thermophysical properties. A serious effort is devoted to the study of effect of variable thermophysical properties on the heat transfer. According to different variations of gaseous specific heat with temperature, heat transfer problems for two kinds of gases are studies separately. The first kind of gases is monatomic and diatomic gases, air and water vapor whose specific heat variation with temperature may be taken as constant, while the second kind of gases is polyatomic gases with variable specific heat. Obviously, the first kind of gases is a special case of the second one. The temperature parameter method is used for simulation of the variations of gaseous thermophysical properties, such as thermal conductivity, viscosity, density, and specific heat with temperature. The temperature parameter methods are so simple that each gas corresponds to its special temperature parameters, such as the thermal conductivity parameter, viscosity parameter, and specific heat parameter. The simulation expressions of the variable thermophysical properties with the temperature parameter method have been conveniently coupled with the dimensionless governing equations of the boundary layers. The effects of the main physical factors including variable thermophysical properties on heat transfer of laminar free convection of gases are clarified by considering large temperature differences. On this basis, the corresponding shortcut formulae are developed for simple and practical prediction of the heat transfer coefficients of laminar free convection of gases.

The second study relates to the free convection of liquids with variable thermophysical properties [69]. A theoretically rigorous approach of the study on heat transfer of free convection of liquids is proposed with the combination of the dimensionless governing equations with the simulation expressions of the variable thermophysical properties. An essential effort is devoted to study free convection of water with large temperature difference. It is concluded that the Prandtl number Pr_∞ at the temperature of the bulk fluid dominates the heat transfer coefficient of the laminar free convection of water. This conclusion is not only simple, but also in close agreement with the rigorous numerical solutions. On this basis, the corresponding shortcut formula is developed for simple and practical prediction of the heat transfer coefficient of water free convection with large temperature differences.

The third study is for film boiling [70] and film condensation [71,72]. These studies are extensive and contain the situations of film boiling of subcooled liquid and film condensation of superheated vapor. A theoretically rigorous approach of studies on heat and mass transfer for the two-phase boundary layers problem is proposed by considering variable thermophysical properties and complicated physical factors on the interface between the liquid and vapor films. An extensive effort is devoted to the study of heat and mass transfer for film boiling of subcooled water and film condensation of superheated water vapor both with large temperature differences. For this purpose, the corresponding mathematical models are systematically developed with the combination of the dimensionless governing equations of the two-phase boundary layers and the simulation expressions of the variable thermophysical properties of gases and liquids. The numerical procedures of the three-point boundary value problem are provided for the film boiling and condensation, respectively, in which the complicated boundary conditions at the interface of the films are rigorously considered. Rigorous numerical results are obtained for large temperature differences. The dimensionless physical property factors and their effects on heat transfer coefficient and mass flow rate are demonstrated. For application purposes, shortcut formulae are developed for the simple and reliable prediction of heat and mass transfer of the film boiling and condensation.

All the earlier-mentioned studies are not only devoted to the heat transfer for vertical plate case, but also for the inclined case [76]. The dimensionless governing equations of the new mathematical models can be used directly to express the inclined plate/surface case, although these do not involve any angle explicitly. In addition, all the transformation relationships for the heat, mass, and momentum transfer from the vertical plate/surface case to the corresponding inclined plate/surface case are derived.

Hydrodynamics and Heat Transfer of Boundary Layer and Film Flows of Non-Newtonian Power-Law Fluids

More recently, Rao [77] measured experimentally the heat transfer in a developed non-Newtonian fluid films falling down a vertical tube. Andersson and Shang [73], Shang and Andersson [74], and Shang and Gu [75] continuously provided extended analysis and numerical calculation for hydrodynamics, heat transfer, and the thermal boundary layer of the boundary layer region of FFNF system on isothermal flat plate. Massoudi and Phuoc [78] supposed a fully developed flow for the FFNF system and on this basis to calculate velocity and temperature fields. Ouldhadda et al. [79, 80] investigated numerically the laminar flow of heat transfer of FFNF on horizontal cylinder with supposition of a simple developed flow region for the FFNF system. However, except a few works, such as of Andersson and Irgens [59, 60], Andersson and Shang [73], Shang and Andersson [74], and Shang and Gu [75], in the most of current studies, the hydraulic entrance region (i.e. the boundary layer region) was ignored in their analysis of modeling and simulation for the FFNF system. Without considering the existing boundary layer region of the FFNF system, it is never possible to capture the adaptive remodeling process of hydrodynamics and heat transfer, and obtain correct calculation for velocity and temperature fields, film thickness, and heat transfer coefficient of the FFNF system.

On the other hand, although a large number of industrial processes involve heat transfer of FFNF system, the related heat transfer information that can be found in the open literature is relatively scarce. The reason is that the study on a system of heat transfer is a difficult point for FFNF due to its complexity, especially its different characteristics in different regions. Additionally, overcoming the difficult point for hydrodynamics and heat transfer study in hydraulic entrance region is the essential prerequisite of the study for the following hydraulic region.

However, studies [74, 75] dealt with the heat transfer of the boundary layer region, the first part of the hydraulic entrance region. With the local Prandtl number Pr_x proposed by Shang and Andersson [74], the following dependence of the thermal boundary layer thickness was found: (1) except for the case when the local Prandtl number Pr_x equals the related critical local Prandtl number Pr_x^*, the thicknesses of velocity and temperature boundary layers are different; (2) if $Pr_x < Pr_x^*$ the velocity boundary layer thickness is less than the temperature boundary layer thickness; and (3) on the contrary, the velocity boundary layer thickness is larger than the temperature boundary layer thickness. Furthermore, they made a series of contributions to the boundary layer region: (1) a novel approach for prediction of length of boundary layer region; (2) rigorous and practical approach for prediction of mass flow rate entrained into the boundary layer; (3) novel prediction approach of friction coefficient C_{f} on surface; (4) correctly calculated the thicknesses of thermal and momentum boundary layers, and on this basis correctly calculated the velocity and temperature fields and heat transfer coefficients; (5) found the dependent factors on velocity and temperature boundary layer thicknesses and heat transfer coefficients; and (6) innovation of a curve-fitted correlation for rigorous and practical calculation of heat transfer coefficient with quite different thicknesses of temperature and velocity boundary layers.

However, the earlier achievements on heat transfer research for the boundary layer region should be extended to the entire hydrodynamic entrance region, and even further to the entire FFNF system. The study should also be extended to include the effects of various boundary conditions, e.g., porous medium, permeable, and soluble wall conditions, and inclined isothermal and constant heat flux surfaces on heat transfer. The studies should also consider the transition regulation from the laminar flow to turbulent flow of the FFNF system, and the effects of temperature-dependent properties on the system of heat transfer coefficients.

1.4.4 Recent Experimental Measurements of Velocity Field in Boundary Layer

Besides the advanced theoretical studies, in this book, we also show recently obtained experimental measurements of velocity field on the boundary layer of the laminar free convection, both of air and water. Very important is that the measurement of velocity field of the boundary layer of the laminar free convection requires a high degree of precision. The difficulty in accurate quantification is very great. In 1930, Schmidt and Beckman measured the velocity field of the laminar free convection of air [81], and hitherto this measurement is taken as classical. Their experimental results were well identical to the corresponding theoretical solutions based on the Boussinesq approximation obtained by Pohlhausen. However, for a long time, there has been a shortage of the experimental results of the velocity field of the boundary layer for the gas laminar free convection with the large temperature difference. Meanwhile, for the velocity field in the boundary layer for the liquid laminar free convection, even in the case of the small temperature differences, there has been a shortage of experimental results. Therefore, our experimental results for the velocity field on the boundary layer of laminar free convection with the large temperature differences for air [82] and water [69,83] are reported in the book. These experimental measurements have been very difficult to obtain. The velocity fields of the laminar free convection of air and water in the case of different temperature differences obtained by the experiments have not only verified the corresponding theoretical results of the free convection for gas and liquid with the large temperature difference mentioned earlier, but also filled in the gaps in the study of the measurement of velocity field of laminar free convection for gases and liquids with the large temperature differences.

These new theoretical and experimental studies introduce a new development for the study of laminar free convection in single and two-phase boundary layers and films under large temperature differences. These are all described in the following chapters of this book. The purpose of this book is to systematically express these results, to promote further development of the study of free convection film flows with large temperature differences, and to satisfy the increasing demands of industry.

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